Effects of burning season on recorded fire temperature and the regeneration of oak species

Elisabeth H. Nadler

Research Advisor: Dr. Roger A. Williams

The Ohio State University

School of Environment and Natural Resources

210 Kottman Hall

2021 Coffey Road

Columbus, Ohio 43210

Submitted: 25 April 2014

THE OHIO STATE UNIVERSITY
COLLEGE OF FOOD, AGRICULTURAL, AND ENVIRONMENTAL SCIENCES

ABSTRACT: The composition of eastern deciduous forests has changed within the last 100 years as a result of decreased natural fire disturbances. The presence of oak (Quercus spp.) has greatly declined, and has been increasingly replaced by maple (Acer spp.) and other shade-tolerant species. This composition shift poses a threat to eastern forest ecosystems. This study focuses on the relationship between season of burn and oak regeneration in contemporary forests. Average recorded fire temperatures were significantly hotter during the fall burns (436.5°C) compared to spring burns (345.8°C). Southern and western aspects had significantly hotter recorded fires compared to northern and eastern aspects within each season of burn. Recorded midslope fires were also significantly hotter than upper and lower slope fires within each season of burn. Oak, a fire-adapted species responded to the higher recorded temperatures by regenerating higher numbers of stems compared to cooler fires one growing season following the burns. Management implications in regard to fire use are discussed.

KEYWORDS: *Quercus, Acer rubrum,* prescribed fire, oak management, burn season, fire intensity, hardwood forests

INTRODUCTION

Oaks (*Quercus* spp.) hold a special place in the ecosystems, economies, and culture of the eastern United States, as well as the world. Many people appreciate these grand trees that have long been a part of the American landscape; some rely on the valuable hardwood oak produces on a daily basis for various needs and activities, or work in the timber industry; still others appreciate viewing the wildlife that oak feeds and houses, such as squirrels, deer, chipmunks, and many species of birds, to name a few. Anthropogenic and aesthetic reasons aside, oaks currently hold an irreplaceable ecological space in the landscape, which cannot be denied. But was this the case 100, 1,000, and 10,000 years ago, and is the oak in danger of losing its dominance on the landscape today?

Historical, dendrochronological, and paleoecological studies have shown oak to be a component of hardwood and mixed forests of North America for most of post-glacial history, occupying much of the eastern landscape for the last 10,000 years (Abrams 1992, Albrecht and McCarthy 2005, Hutchinson et al. 2008). Some of the same studies have concluded that the presence of oak increased in presettlement forests as a result of Indian burning practices and other disturbance factors, and continued to increase through the European settlement era (Abrams 1992). Burning, logging, and clearing encouraged the abundant growth of oaks (an early to mid successional species) on the landscape during this time. Now in the early 21st century, we find that many oak-hickory forests are losing dominance to other species such as maple (*Acer* spp.) and that overall there is a lack of oak regeneration at the ground level. According to various studies, oaks are not well represented past the stem-exclusion stage, if at all, in many eastern hardwood stands at present (Abrams 1992; Lorimer 1994; Hutchinson 2008). This shift has been a point of concern for many, yet long-term ramifications of such a composition shift on its ecosystems are unknown to researchers at this time.

The cause for this shift may be aggravated by many factors, but it is widely regarded that the main historical link to oak dominance is periodic fire to which it is adapted (Abrams 1992; Hutchinson et al. 2008; Arthur et al. 2012). Oaks have thick, fire-resistant bark, are able to compartmentalize wounds, and sprout after being top-killed. Furthermore, they possess a resistance to rotting after scarring, and fire creates optimal seedbeds for acorn germination; therefore, oak is better adapted to a periodic fire regime than maple (Abrams 1992 and Hutchinson et al. 2008). As seedlings, oaks have hypogenous (below ground) germination, thus their root collars are protected in a fire relative to many of their competitors with epigenous (above ground) germination. Moreover, oak invests more energy into root system development in their early growth stages; post-fire, new sprouts have a competitive advantage compared to the initial stem and competitors due to the already present and well-developed root system. These and other characters allow for the successful dominance of oak following a fire.

Since the adoption of legislation and policies to control forest fires in 1923, there has been a notable loss in the number of oak stems, which have been increasingly replaced by individuals of species that historically did not dominate in eastern forests (Hutchinson et al. 2008). These competitor species, such as red maple (*Acer rubrum)*, yellow-poplar (*Liriodendron tulipfera*), and sassafras (*Sassafras albidum*), possess qualities that allow them to out-compete oak in the absence of fire, such as a greater shade tolerance or faster growth rate compared to the slow growing, mid-tolerant oak

(Hutchinson et al. 2008). Dendrochronology was used in a study that found virtually no oak recruitment occurring after the year 1925; the vast majority of present maple trees were established after this year (Hutchinson et al. 2008).

There is concern that without any large-scale, periodic disturbance, many eastern forest stands could see a permanent shift to shade-tolerant species in place of the historically dominant oak. It is true that other factors including climate change, animal grazing, insects, logging, and disease have altered the oak-dominance in these forests, but most of the change can be directly connected to historical changes in the fire regime (Abrams 1992, Alexander and Arthur 2009). Besides fire, there are not any other current large-scale disturbances such as ice storms or catastrophic blow downs that could support oak regeneration over time (Albrecht and McCarthy 2005).

Gaining better ecological and specific knowledge concerning the relationship of fire and oak regeneration is increasingly more important as public agencies and forest managers continue to increase the amount of acres scheduled for prescribed burns on public lands in an effort to restore oaks. We must therefore ask before continuing this process, does using fire as a management tool in forests effectively accomplish the specific ecological and silvicultural objectives it is intended for? Some argue that the composition of eastern forests has changed to such an extent that a prescribed burn will not produce oak regeneration naturally, which many individuals have found in failed attempts to use fire to restore oaks (Albrecht and McCarthy 2005; Signel et al. 2005; Dumas et al. 2007).

Arthur et al. (2012), along with many other researchers call for “improved knowledge of when to apply fire in the life cycles of oaks and the key competitors for various stages of stand development." It is such an end that this particular research project seeks; this need for more information about the oak/fire relationship has prompted a more in-depth study in order to effectively use fire as a tool to restore oaks in eastern ecosystems. Research has been conducted on various aspects of the oak and fire relationship, including paleoecological analysis of wetland sediments (Delcourt et al 1998), dendrochronological studies (Sutherland 1997; McCarthy et al 2001), and witness tree records (Dyer 2001), but there is a lack of information concerning the effect that the season of burn has on oak regeneration. Understanding the influence of season of burn on oak regeneration is a major asset in understanding how fire and regeneration are related, and if it is possible to use fire as an instrument to restore oak.

With this obvious lack of information regarding the effects of fire season on eastern forests, burn data collected from 4 burns in 3 forests in southern Ohio (part of the historical region of oak) were analyzed to address the following objectives:

1. Determine if season of burn (Fall v. Spring) influences fire temperature, accounting for slope position and aspect
2. Determine if season of burn (Fall v. Spring) differs in favoring oak regeneration over other species
3. Examine the response of both species *Acer rubrum* and *Quercus* spp. post burn as stump sprouts versus seedlings

It is imperative to gain a deeper understanding of the contemporary oak-fire relationship along with competitor response, if oak is to be successfully regenerated and maintain their important role in eastern forest ecosystems.

METHODS

Data utilized for this study were collected in two previous experiments conducted in 2004, and 2009 through 2010 (Schwemlin 2006, Silvis 2011). The first study was conducted in Richland Furnace (39°10'N, 82°36'W) and Tar Hollow (39°22'N, 82°45'W) State Forests, and the second study occurred at Richland Furnace and Zaleski State (39°17' N 82°23' W) Forests. All of these State Forests are located in southern Ohio, where the landscape is unglaciated and characterized by rolling hills and ravines. All are mixed hardwood forests with recorded oak dominance.

The 2004 study measured oak (*Quercus* spp.) and red maple (*Acer rubrum*) stems before and after burns were conducted on 32 research plots. Three seedling stems of seed origin for each species group (oak and red maple) were selected to be monitored at each plot. Prior to the burns, stem size attributes for each stem were measured, including total height (cm), diameter at breast height (DBH, mm) and diameter at the root collar (DRC, mm). Stems showing signs of dieback, disease, excessive root suckering, or excessive forking were avoided. Sample stems were labeled with a numbered tag for relocation after the burn. Furthermore, topographical information was recorded for each plot, including percent slope, aspect of slope, and slope position (by thirds). For aspect measurements, north was considered 315° - 44°, east as 45° - 134°, south as 135° - 224°, and west as 225° - 314°. To record temperature information from the burns, pyrometers were placed at the uphill base of each stem. These pyrometers were comprised of tags with Tempilaq® temperature-sensitive paint at three levels above the soil surface- 0, 20, and 40 cm. There were ten paints with different melting points (79°, 93°, 121°, 149°, 177°, 204°, 260°, 316°, 427°, and 538°C) on each tag; the last paint to melt provided the maximum temperature range reached during the fire. Therefore, in analysis the melting point (e.g. 121°C) of the last melted paint was used as the recorded temperature. Fuel loads were recorded pre-burn with a fine litter measurement tool to the nearest 0.01 cm. One growing season following the fires, the tree samples were revisited and assessed for mortality by three categories: alive, top-killed, or dead. Stems were also examined for the presence of any sprouts, of which total number and height were recorded if present. Finally, canopy cover and basal area of the overstory were recorded at each plot after the burn.

In the 2009-2010 study, 192 stumps were examined from 64 plots. In each plot, three stumps were chosen to be monitored for sprout clusters: one from a red oak species group (*Quercus rubra, Q. velutina,* or *Q. coccinea)*, a white oak species group (*Quercus alba* or *Q. prinus),* and a red maple. The total number of sprouts in the cluster was noted, and one random sprout was selected, tagged, and measured for height and DBH. These study plots were located in a portion of the forests where shelterwood harvests had been conducted in 2005 with 70% and 50% retention rates. This study included both fall and spring burns. To measure the temperature of the fire levels during the burn, the same type of pyrometers using heat-sensitive paint tags as in the previous study were placed at the base of each stump at 0, 20, and 40 cm, similar to the 2004 study. After a full growing season following the prescribed burns, the stumps were revisited to determine if the original sprouts were unharmed, damaged, top-killed, or entirely killed by the fire. Furthermore, any new post-burn sprouts were counted, and a random sprout was selected and measured for its height and DBH. Overall, data from four burns (two spring and two fall) were utilized in the following analyses.

The data from both studies were analyzed using ANOVA and Duncan's multiple range test in SAS, ver. 9.2 (SAS 2008). Analyses included comparison of recorded temperatures at the different height levels (0 cm, 20 cm, 40 cm, and average) for season, slope position, and aspect.

RESULTS

Fall burns were significantly hotter than spring burns at all measurement heights. The greatest difference in recorded temperature between seasons was 20 cm above the ground.

Table 1. The mean[1] recorded temperature (°C) of fall, spring, and all burns combined by average temperature and measurement height (ground, 20 cm, 40 cm).

Season	N	Avg	Temp0	Temp20	Temp40
Fall	50	436.5A	611.3A	440.4A	276.2A
Spring	53	345.8B	521.6B	304.3B	230.3B

[1] Means followed by the same letter are not significantly different between season of burn at p=0.05, Duncan's MRT.

On all aspects, the mean temperature of fall burns was significantly hotter than spring burns. Fall burns on north- and west-facing slopes were significantly hotter than spring burns at 0 cm, 20 cm, and on average. On south-facing slopes, fall burns were significantly hotter than spring burns at the higher measurements (20 and 40 cm) but not at the ground level. Fall burns on east-facing slopes were not significantly hotter at all three measurement levels, yet average recorded fall temperature was still hotter than average recorded spring temperature.

Table 2. The mean[1] recorded temperature (°C) of fall and spring burns at three heights combined by aspect (east, north, south, and west).

Aspect	Season	N	Average Temp	0	20	40
East	Fall	31	361.0A	531.5A	353.2A	207.4A
	Spring	37	321.9B	493.4A	273.0A	198.4A
North	Fall	28	392.3A	571.4A	387.5A	217.9A
	Spring	25	250.3B	401.0B	219.0B	131.0A
South	Fall	43	510.9A	680.6A	535.2A	368.6A
	Spring	46	428.3B	620.2A	378.3B	294.5B
West	Fall	45	444.8A	620.1A	440.6A	277.8A
	Spring	33	330.1B	506.8B	300.8B	241.2A

[1] Means followed by the same letter are not significantly different between season of burn within aspect at p=0.05, Duncan's MRT.

For both seasons the greatest mean recorded temperatures were reached at the mid-slope level. Upper slopes had the next hottest recorded temperatures, and lower slope had the least hot recorded temperatures. In spring, there were significantly different temperatures at all slope positions; in fall, only the middle slope was significantly different from the upper and lower slopes.

Table 3. The mean[1] recorded temperature (°C) of upper, middle and lower slope burns combined by season of burn.

Position	Combined	N (Fall)	Fall	N (Spring)	Spring
Upper	380.39B	55	421.52B	61	343.31B
Middle	537.80A	42	529.56A	27	550.62A
Lower	307.61C	50	374.67B	53	244.34C

[1] Means followed by the same letter are not significantly different between slope position at p=0.05, Duncan's MRT.

Fall burns were significantly hotter than spring burns at upper slope and lower slope positions, but not at the middle slope position.

Table 4. The mean[1] recorded temperature (°C) of fall and spring burns according to slope position.

Season	N (U)	Upper	N (M)	Middle	N (L)	Lower
Fall	55	421.5A	42	529.6A	50	374.7A
Spring	61	343.3B	27	550.6A	53	244.3B

[1] Means followed by the same letter are not significantly different between slope position at p=0.05, Duncan's MRT.

A significantly greater number of oak seedlings was found after fall burns than spring burns (table 5). For oak stump sprouts, no significant difference was determined between fall and spring burns. For red maple, significantly more seedlings occurred after fall burns than spring burns, but for stump sprouts there was no significance difference between seasons. Overall, fall burns showed no significant difference in the regeneration of red maple, but did show a significant increase in oak regeneration, compared to spring burns. Even though fall burns were more successful at regenerating oaks in a combined analysis versus spring burns, it should be noted that for all burns and seasons and sprout types, red maple outnumbered oak, even when oak showed a significant change and red maple did not. The only season in which there was no significant difference in the number of sprouts was for spring stump sprouts; all of the other seasons and sprout types were significantly different in number of sprouts between oak and red maple.

Table 5. The mean[1] number of seedling sprouts, stump sprouts, and both sprout groups one growing season following a burn combined by species and season of burn.

Sprout type	Species	Season	N	Number of sprouts
Seedling	Oak	Fall	38	3.61 aB
		Spring	47	2.26 bB
	Red maple	Fall	40	7.23 aA
		Spring	46	6.09 bA
Stump	Oak	Fall	34	5.18 aB
		Spring	24	5.21 aA
	Red maple	Fall	31	7.03 aA
		Spring	30	6.17 aA
Combined	Oak	Fall	72	4.35 aB
		Spring	71	3.25 bB
	Red maple	Fall	71	7.14 aA
		Spring	76	6.12 aA

[1] Means followed by the same lower-case letter are not significantly different between season of burn within species at p=0.05, Duncan's MRT. Means followed by the same upper case letter are not significantly different between the two species within season of burn at p=0.05, Duncan's MRT. Fall oak seedling corresponds with fall red maple seedling, etc.

Fall burns elicited a higher ratio of oaks to red maples for seedlings and combined regeneration. Stump sprouts had a higher oak to red maple ratio for spring burns. The stump sprouts post spring burn had the highest ratio of oak to red maple overall.

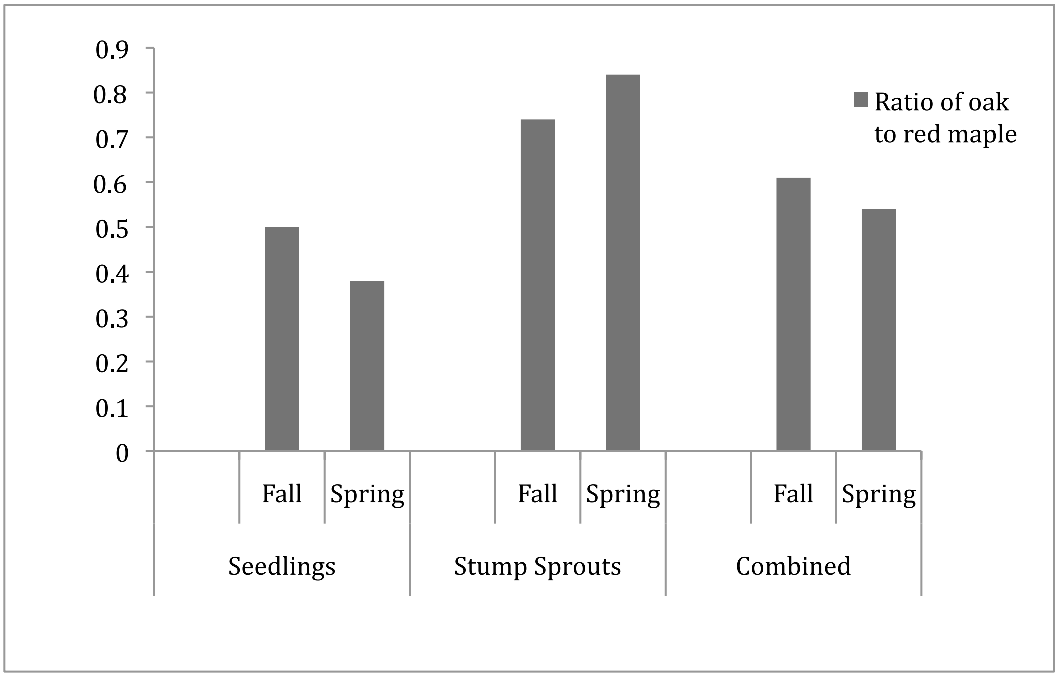

Figure 1. Ratio of oak to red maple seedlings, stump sprouts, and combined regeneration for one growing season after fall and spring burns.

DISCUSSION

The reason for temperature differences between burn seasons and site attributes may be manifold, and the observed effectiveness of fall burns overall holds a number of implications. Sparks et al. (2002) compared growing versus dormant season burns in shortleaf pine forests. They found that dormant season fires had a greater overall fuel load than growing season fires, thus contributing to the greater temperature in the dormant season fires. Accordingly, in the forest stands for this study, large quantities of uncompacted, dry leaf litter existed in the fall, compared to wetter and more compacted leaf litter found in the spring; this is one reason fall fires reached more intense temperatures. This is also because less compacted fuels allow for more integration of oxygen within the fuel layer. In addition, fall fuels are less decomposed compared to fuels allowed to overwinter, providing a greater surface to volume ratio in the fuel.

More evidence points that oak may have adapted over their long-standing presence on this landscape to respond more favorably to fall wildfires. Arthur et al. (2012) note that for a prescribed burn to effectively result in oak regeneration, it must occur during one of the plant's critical life stages, which include pollination, flowering, seed set, germination, establishment, seedling development, and release into the canopy. These life stages vary according to season and size of an oak tree, but a fall burn would allow for increased success of the germination, establishment, development, and release stages because of the preparation of a quality seed bed and elimination of competition at the start of the next growing season. Overall, the findings from this study are different than those of Hutchinson et al. (2005) who conducted a similar study in some of the same forest areas; they suggest late spring burning. These differences in suggested intervals of burning may come from a number of different sources, and indicate that the issue still needs further study. These sources may include different data collection methods and site characteristics at time of data collection.

The results of this study give evidence that burning in the fall instead of the spring is more likely to give oak a better competitive advantage at these sites, as seen in the significant increase in oak sprouts in the combined analysis, whereas red maple had no significant increase (Table 5). Oak's response to a fall burn compared to red maple's is a helpful piece of evidence for managers looking to use fire to restore oak. However, it is not as simple as conducting burns in the fall. In this location, despite the increase in oak regeneration maple still greatly outnumbers oak. Therefore, we need to understand if the use of prescribed fire gives oak enough of a competitive edge (likely by a particular difference in size) against its competitors in an ecosystem where it is so greatly outnumbered, and how particular burn practices may augment its potential success. Looking at the sprout type responses is one way pursued in this study, as seen in the results (Table 5, Figure 1). Sprouts originating from stumps instead of seedlings gave oak a more competitive edge to maple (almost 1:1), whereas the seedling ratio was much lower (about 1:2). While older trees stop producing stump sprouts after a certain point, the findings from this study point towards burning in areas where stumps are abundant, perhaps after a harvest. Another tool for predicting oak sprouting success post clear-cut (a disturbance) are given in a study by Weigel and Peng (2002), which showed that parent tree age and diameter at breast height (DBH) are both significant predictors of sprouting success. Determining the threshold between oak success and failure versus its competitors is one area of pursuit for a future study.

The data from this study also supports the hypothesis that slope position and aspect affect fire temperature. For the spring burns there was a significant difference in temperature at all three slope positions, but in the fall burns only the middle slope was significantly different in temperature from the lower and upper slopes (Table 3). Leaf litter is known to aggregate at the midslope level and is a likely cause of the increased temperatures at this slope position. These findings further exemplify differences between fall and spring burns, and are upheld by data from another study, which indicated that the spatial structure of fuel as well as topography affects the fire intensity, severity, and spatial structure (Franklin et al. 1997). This fuel arrangement and particular topography lends support to the idea that oaks are more likely to be successfully regenerated on middle and upper slopes, and those facing south and west (Tables 2 and 3) due to the higher observed temperatures. However, other factors may need to be accounted for, such as amount of sunlight and soil moisture that can affect oak success.

As mentioned, efforts to restore oaks to previous densities have been met with difficulties (Albrecht & McCarthy 2006; Blankenship & Arthur 2006); it has been shown that spring fires in the early growing season at low intensities can alter seedling leaf characteristics, but not to the extent that provides oak with a competitive advantage relative to red maple and sassafras (Alexander and Arthur 2009). In another study which examined thinning, prescribed fire, and a combination of these methods in mature forests for their efficacy in releasing oaks, it was determined that red maple quickly returned to pre-treatment levels and that oak was unresponsive in all treatments. These treatments were applied in March and April (Albrecht and McCarthy 2005). They found that repeated spring burning in mesic forest openings had little impact on the net growth of northern red oak regeneration, but it adversely affected that of two common competitors, sugar maple and white ash. In this study, there was a significant effect on oak's competitor red maple (Table 5), but the evidence suggests that red maple still has the competitive advantage post-burn. Kruger and Reich (1997) found that existing oak grew as rapidly as ash and maple on average, but even the fastest growing oaks were outnumbered due to the abundance of competitors, maple in particular (150 000 individuals/ha). This ever-increasing bank of knowledge points toward a need to use other methods along with fire and to gain a deeper understanding of which season of burn best allows oak to successfully outcompete oak. Although sometimes unpopular to the public, clearcutting or other forestry practices such as the seed-tree or shelterwood methods may be necessary. Overall, the evidence from this study points to using fall burns in areas with stumps, but further studies should be conducted to confirm the findings.

Limitations and Areas for Future Study

Limitations of this study were greatest among the data collected on regeneration; because the data came from two separate studies with slightly different methods, and part of the data collection included stump sprouts, whereas the other included seedlings and seedling sprouts. These types of regeneration do not necessarily respond to fire in the same way. The scope of this study was another limitation- data was collected from four burns total, which leaves room for more burns to confirm the findings of this study. It would be greatly beneficial to this study to return to the study areas and determine the success of the oak specimens in relation to its competitors now that a number of growing seasons have passed.

Another aspect of burn season not studied but to be addressed is the effect of burn season on wildlife. Due to variations in wildlife strategies such as mating and hibernation between seasons (as well as among species), it is very possible that burning in the spring versus the fall could influence wildlife populations. There are few studies that focus on this topic, which adds importance to the study of a prescribed burn season's effects on ecosystems. Wildlife response to the burn seasons may be a key to understanding the historical occurrence of fires to which these species are adapted.

Management Recommendations

Current forests lacking a recent fire regime are reflecting a late-successional ecosystem where maple dominates instead of the early to mid-successional oak. In order to return to an oak-dominated ecosystem, it would be wise for managers to employ the following recommendations based on this and other studies, including historical evidence. One recommendation is to ensure the fire reaches an intensity to limit midstory trees, which following the evidence of this study would be a burn during the fall season due to its greater intensity. McDonald et al. (2003) found that oak establishment seems to be most limited by the trees in the midstory and not the overstory or understory trees. A higher temperature burn has more chance of affecting the midstory trees. Another recommendation is to conduct repeated burnings at small intervals, perhaps for a number of fall seasons in a row, and then allow for larger intervals in between with no fire (McEwen et al. 2007), or to allow partial grazing to occur in place of fires where necessary. All of these suggestions rely on an intermediate disturbance regime, with occasional large disturbances.

ACKNOWLEDGEMENTS

I would like to thank Dr. Roger A. Williams for his guidance and support, as well as The Ohio State University School of Environment and Natural Resources for the opportunity to conduct research. A special thanks goes out to Doug Schwemlein and Alexander Silvis for gathering the field data and allowing me to work with it for this Honors research project. Finally, I offer my gratitude to my Honors Committee for their participation and review of this project: Dr. David M. Hix, Dr. Stephen N. Matthews, and Mr. Daniel A. Yaussy.

LITERATURE CITED

Abrams, M. D. 1992. Fire and the development of oak forests. *Bioscience* 42(5): 346-353.

Albrecht, M. A. and B. C. McCarthy. 2005. Effects of prescribed fire and thinning on tree recruitment patterns in central hardwood forests. *Forest Ecology and Management* 226: 88-103.

Alexander, H. D., and M. A. Arthur. 2009. Foliar morphology and chemistry of upland oaks, red maple, and sassafras seedlings in response to single and repeated prescribed fires. *Canadian Journal of Forest Research* 39: 740-754.

Arthur, M. A., H. D. Alexander, D. C. Dey, C. J. Schweitzer, and D. L. Loftis. 2012. Refining the oak-fire hypothesis for management of oak-dominated forests of the Eastern United States. *Journal of Forestry* 110: 257-266.

Blankenship, B. A. and M. A. Arthur. 2006. Stand structure over 9 years in burned and fire-excluded oak stands on the Cumberland Plateau, Kentucky. *Forest Ecology and Management* 225: 134-145.

Delcourt, P. A., H. R. Delcourt, C. R. Ison, W. E. Sharp, and K. J Gremillion. 1998. Prehistoric human use of fire, the eastern agricultural complex, and Appalachian oak-chestnut forests; paleoecology of Cliff Palace Pond, Kentucky. *American Antiquity* 63(2):263

Dyer, J. M. 2001. Using witness trees to assess forest change in southeastern Ohio. *Canadian Journal of Forest Research* 31(10): 1708-1718.

Dumas, S., H. S. Neufeld, and M. C. Fisk. 2007. Fire in a thermic oak-pine forest in Linville Gorge Wilderness Area, North Carolina: importance of the shrub layer to ecosystem response. *Castanea* 72(2): 92-104.

Franklin, S. B., P. A. Robertson, and J. S. Fralish. 1997. Small-scale fire temperature patterns in upland *Quercus* communities. *Journal of Applied Ecology* 34:613-630.

Hutchinson, T. F., R. P. Long, R. D. Ford, E. K. Sutherland. 2008. Fire history and the establishment of oaks and maples in second-growth forests. *Canadian Journal of Forest Research* 38: 1184-1198.

Hutchinson, T. F., R. E. J. Boerner, S. Sutherland, E. K. Sutherland, M. Ortt, and L. R. Iverson. 2005. Prescribed fire effects on the herbaceous layer of mixed-oak forests. *Canadian Journal of Forest Research* 35: 877-890.

Kruger, E. L and P. B. Reich. 1997. Responses of hardwood regeneration to fire in mesic forest openings. III. Whole-plant growth, biomass distribution, and nitrogen and carbohydrate relations. *Canadian Journal of Forest Research* 27: 1841-1850.

Lorimer, C. G., J. W. Chapman, and W. D. Lambert. 1994. Tall understorey vegetation as a factor in the poor development of oak seedlings beneath mature stands. *Journal of Ecology* 82(2): 227-237.

McCarthy, B C., C. J. Small, and D. L. Rubino. 2001. Composition, structure and dynamics of Dysart Woods, an old-growth mixed mesophytic forest of southeastern Ohio. *Forest Ecology and Management* 140(2): 193-213.

McDonald, R. I., R. K. Peet, and D. L. Urban. 2003. Spatial pattern of *Quercus* regeneration limitation and *Acer rubrum* invasion in a Piedmont forest. *Journal of Vegetation Science* 14(3): 441-450.

McEwan, R. W., T. F. Hutchinson, R.P. Long, R. D. Ford, and B. C. McCarthy. 2007. Temporal and spatial patterns in fire occurrence during the establishment of mixed-oak forests in Eastern North America. *Journal of Vegetation Science* 18(5): 655-664.

SAS Institute 2008. Statistical Analysis Software, version 9.2, Cary, NC, USA

Schwemlin, D. J. 2006. Impacts of burn season and topographic position on the first year response of oak and red maple regeneration to prescribed fire in southern Ohio. Ohio State University School of Environment and Natural Resources Master's Thesis. pp 109.

Silvis, A. 2011. The response of bats to shelterwood harvest and prescribed fire. Ohio State University School of Environment and Natural Resources Master's Thesis. pp 123.

Signell, S. A., M. D. Abrams, J. C. Hovis, and S. W. Henry. 2005. Impact of multiple fires on stand structure and tree regeneration in central Appalachian oak forests. *Forest Ecology and Management* 218: 146-158.

Sparks, J. C., R. E. Masters, D. M. Engle, G. A. Bukenhofer. 2002. Season of burn influences fire behavior and fuel consumption in restored shortleaf pine—grassland communities. *Restoration Ecology* 10(4): 712-722.

Sutherland, E. K. 1997. History of fire in a southern Ohio second-growth mixed-oak forest. *United States Department of Agriculture Forest Service General Technical Report NC* 188: 172-183.

Weigel, D. R. and C. J. Peng. 2002. Predicting stump sprouting and competitive success of five oak species in southern Indiana. *Canadian Journal of Forest Research* 32: 703-712.